# REPORT DOCUMENTATION PAGE

| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | November 1995 | technical |

**4. TITLE AND SUBTITLE**

Development of an Integrated Process Planning/Production Scheduling Shell for Agile Manufacturing

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**

Norman M. Sadeh, Thomas J. Laliberty, Robert V.E. Bryant, and Stephen F. Smith

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213

**8. PERFORMING ORGANIZATION REPORT NUMBER**

CMU-RI-TR-95-40

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION / AVAILABILITY STATEMENT**

Approved for public release;
Distribution unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** (Maximum 200 words)

As companies increase the level of customization in their products, move towards smaller lot production and experiment with more flexible customer/supplier arrangements such as those made possible by Electronic Data Interchange (EDI), they increasingly require the ability to (1) quickly, accurately and competitively respond to customer requests for bids on new products and (2) rapidly and effectively work out supplier/subcontractor arrangements for these new products. This in turn requires the ability to (1) rapidly convert standard-based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines, fixtures and tools, and the availability of raw materials.

This paper summarizes initial work towards the development of an Integrated Process Planning/Production Scheduling (IP3S) Shell for Agile Manufacturing. The IP3S Shell is designed around an innovative blackboard architecture that emphasizes (1)concurrent development and dynamic revision of integrated process planning/production scheduling solutions, (2) the use of a common representation for exchanging process planning and production scheduling information, (3) coordination with outside information sources such as customer and supplier sites, and (4) mixed initiative decision

**14. SUBJECT TERMS**

Keywords: Agile Manufacturing, Production Scheduling, Process Planning, Blackboard Architecture, Computer Integrated Manufacturing, Supply Chain Coordination

**15. NUMBER OF PAGES**

11 pp

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| unlimited | unlimited | unlimited | unlimited |

# DEVELOPMENT OF AN INTEGRATED PROCESS PLANNING/PRODUCTION SCHEDULING SHELL FOR AGILE MANUFACTURING[1]

Norman M. Sadeh *, Thomas J. Laliberty**,
Robert V.E. Bryant**, and Stephen F. Smith*
November 1995
CMU-RI-TR-95-40

Intelligent Coordination and Logistics Lab*
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3890

Raytheon Company**
Electronic Systems Division
Electronic Systems Laboratory
Tewksbury, MA 01876-0901

19960719 075

---

# ABSTRACT

As companies increase the level of customization in their products, move towards smaller lot production and experiment with more flexible customer/supplier arrangements such as those made possible by Electronic Data Interchange (EDI), they increasingly require the ability to (1) quickly, accurately and competitively respond to customer requests for bids on new products and (2) rapidly and effectively work out supplier/subcontractor arrangements for these new products. This in turn requires the ability to (1) rapidly convert standard based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines, fixtures and tools, and the availability of raw materials.

This paper summarizes initial work towards the development of an Integrated Process Planning/Production Scheduling (IP3S) Shell for Agile Manufacturing. The IP3S Shell is designed around an innovative *blackboard architecture* that emphasizes (1)*concurrent* development and dynamic revision of integrated process planning/production scheduling solutions, (2) the use of a *common representation* for exchanging process planning and production scheduling information, (3) *coordination* with outside information sources such as customer and supplier sites, and (4) *mixed initiative decision support,* enabling the user to interactively explore a number of tradeoffs. The system is scheduled for initial demonstration in a large and highly dynamic machine shop at Raytheon's Andover manufacturing facility.

**Keywords**: Agile Manufacturing, Production Scheduling, Process Planning, Blackboard Architecture, Computer Integrated Manufacturing, Supply Chain Coordination

# 1. INTRODUCTION

Over the past two decades, considerable efforts have been expended in developing integrated Computer Aided Design/Computer Aided Manufacturing functionalities (e.g., [Harrington74, Rembold86, Scheer91]). Simultaneously, important progress has been made towards the development of integrated production planning and control solutions (e.g., [Orlicky75, Goldratt80, Smith92b, Sadeh94a]), integrated sales/marketing solutions, etc. leading to what we can view as "islands of integration" within the enterprise [Kerr91]. While the actual level of integration within each island can significantly vary from one enterprise to another, and important progress still remains to be made within each of these areas, building the bridges between these islands is without any doubt the next major hurdle in developing Computer Integrated Manufacturing environments capable of effectively supporting Agile Manufacturing practices.

As companies increase the level of customization in their products, move towards smaller lot production and experiment with more flexible customer/supplier arrangements such as those made possible by Electronic Data Interchange (EDI) [Lee92, Srinivasan94, Swaminathan94, Goldman95], they increasingly require the ability to (1) quickly, accurately and competitively respond to customer requests for bids on new products (i.e., quality, costs, delivery dates, etc.) and (2) rapidly and effectively work out supplier/subcontractor arrangements for these new products. This in turn requires the ability to (1) rapidly convert standard-based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines, fixtures and tools, and the availability of raw materials. A key element in effectively supporting such capabilities requires bridging the integration gap between CAD/CAM and production scheduling through the development of integrated process planning/ production scheduling functionalities.

This paper summarizes initial work towards the development of an Integrated Process Planning/Production Scheduling (IP3S) Shell for Agile Manufacturing. The IP3S Shell is designed around an innovative *blackboard architecture* [Erman80,Stefik81,Nii86,Smith94] that emphasizes:

(1) *concurrent development and dynamic revision of integrated process planning/production scheduling solutions*, using new analysis and diagnosis tools that enable efficient process plan development through early consideration of resource capacity and production constraints (e.g. taking into account the current load of the facility) and greater optimization of production activities through direct visibility of process alternatives and

tradeoffs. This contrasts with existing manufacturing practice where process planning and production scheduling are treated as independent activities carried out in a rigid, sequential manner. Instead, concurrent development and revision of integrated IP3S solutions is expected to (a) significantly enhance the ability of manufacturing companies to efficiently adapt to changing conditions (both internal and external) and (b) yield significant performance improvements (leadtimes, due date performance, resource utilization, inventories, coordination with customers and suppliers, etc.)

(2) the use of a *common representation* for exchanging process planning and production scheduling information

(3) a *control infrastructure* for managing interactions between process planning and production scheduling and support integration with outside information sources (e.g. supplier and customer nodes)

(4) *mixed initiative decision support* making it possible for the user to explore alternative tradeoffs ("what-if" scenarios) by interactively imposing and/or retracting various assumptions (e.g. process restrictions, alternative delivery dates, machine assignments, etc.) and evaluating the impact of these decisions through incremental process plan/production schedule modification.

Our approach builds from existing component technologies, namely Raytheon's ICAPP process planning system [Raytheon93a,b] and Carnegie Mellon's Micro-Boss scheduling system [Sadeh93b,Sadeh94a]. The two systems are integrated as knowledge sources within the blackboard architecture. The resulting IP3S Shell is scheduled for initial demonstration and evaluation at Raytheon's Andover machine shop. This is a complex, highly dynamic, small-lot manufacturing environment that includes over 80 CNC machine tools, and requires the construction of about 500 new process plans a year, each requiring an average of 6 tool designs/modifications.

## 2. INTEGRATING PROCESS PLANNING AND PRODUCTION SCHEDULING

Technical challenges in effectively supporting integrated process planning/production scheduling decisions in a complex and dynamic environment such as Raytheon's machine shop are multiple. Even from a pure process planning perspective the sheer variety of parts, number of orders requiring the generation of new process plans and production of new tools, and finally the variety of machines and their various characteristics present a challenge in their own right. As in other large machine shops, production scheduling in this environment is no easy task either. Major scheduling challenges include (1) the presence of multiple sources of uncertainty, both

internal (e.g., machine breakdowns) and external (e.g., new order arrivals, raw material deliveries, etc.), (2) the difficulty in accurately accounting for the finite capacity of a wide array of machines operating according to complex constraints (e.g., setup constraints), and (3) the need to take into account the multiple resource requirements of various operations (e.g., tools, fixtures, NC programmers, raw materials, etc.).

While considerable progress has been made with respect to software technologies for process planning and finite-capacity production scheduling, very little attention has been given to issues of integration. Except for a few integration attempts in the context of small manufacturing environments (e.g., [Aanen88, Bossink92]), process planning and production scheduling activities are typically handled independently, and are carried out in a rigid, sequential manner with very little communication. Process alternatives are traded off strictly from the standpoint of engineering considerations, and plans are developed without consideration of the current ability of the shop to implement them in a cost effective manner. Likewise, production scheduling is performed under fixed process assumptions and without regard to the opportunities that process alternatives can provide for acceleration of production flows. Only under extreme and ad hoc circumstances (e.g., under pressure from shop floor expediters of late orders), are process planning alternatives revisited. This lack of coordination leads to unnecessarily long order lead times, increased production costs and inefficiencies and severely restricts the ability to effectively coordinate local operations with those at supplier/customer sites, whether internal (e.g., tool shop, enterprise-level planning system) or external (e.g., raw material suppliers).

## 3. THE IP3S BLACKBOARD ARCHITECTURE

The use of blackboard architectures as a vehicle for integrating multiple knowledge source modules to solve complex problems has been demonstrated in a variety of application domains (e.g., speech understanding, scene recognition, factory scheduling, etc.). Our approach builds on architectural concepts developed in the context of the OPIS/DITOPS scheduling system [Smith94] and includes Knowledge Sources based on Raytheon's ICAPP process planning system [Raytheon93a,b] and Carnegie Mellon's Micro-Boss scheduling system [Sadeh94].

Through their emphasis on modular encapsulation of problem solving knowledge in independent knowledge sources that communicate through a shared data structure (blackboard) and their explicit separation of domain knowledge (e.g., process planning/production scheduling knowledge in this case) and control knowledge, blackboard architectures offer several key advantages:

- *extensibility* of the architecture, making it particularly easy to progressively add or enhance knowledge sources (e.g., add new analysis knowledge sources to support mixed initiative planning/scheduling functionalities)

- *flexibility* of the control procedure, allowing for support of and experimentation with multiple control regimes (e.g., mixed-initiative control regime where the user decides which knowledge source to activate next as well as generative and reactive control regimes).
- *re-usability* of knowledge sources (e.g. analysis/diagnosis knowledge sources) across multiple manufacturing environments
- *integration of legacy systems* (e.g. companies can build on existing process planning and/or production scheduling modules).

The architecture of the Integrated Process Planning/Production Scheduling module is shown in Figure 1. It consists of (1) several knowledge sources, including a process planning knowledge source based on Raytheon's ICAPP process planner, a production scheduling knowledge source based on Carnegie Mellon's Micro-Boss production scheduling system, a communication knowledge source and several analysis/diagnosis knowledge sources, (2) a shared data structure (blackboard) through which the knowledge sources communicate and (3) a search control mechanism (IP3S Controller) that determines, either automatically or through interaction with the user, which knowledge source to activate next.
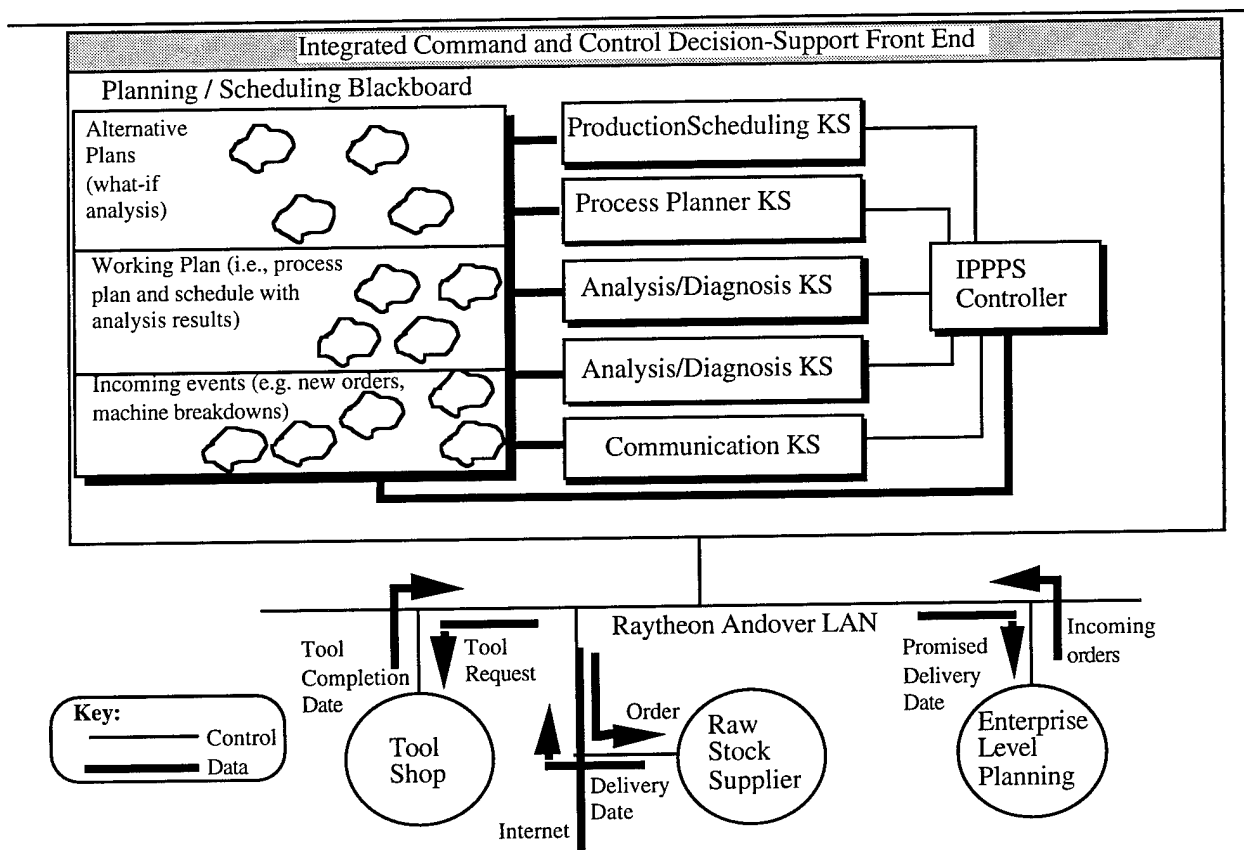


**Figure 1: The IP3S Blackboard Architecture**

The blackboard is the shared data structure through which knowledge sources communicate, exchanging, critiquing and modifying complete and partial solutions. It is the repository of the current working solution (process plans and schedules), analysis results, alternative complete and partial solutions (generated through automated search, interactions with the user, or both) and also stores incoming event descriptions (e.g., incoming orders, expected tool completion dates, machine breakdowns, scheduled maintenance etc.). The blackboard also provides a common representation of process planning and production scheduling entities, constraints, objectives and preferences (e.g., machine representations, production costs, tool requirements, etc.).

Different elements of the IP3S architecture are further detailed below.

## The IP3S Controller

The IP3S Controller directs solution construction and revision by deciding at each step which Knowledge Source to activate next (e.g., activating a specific analysis KS, requesting the process planning KS or production scheduling KS to expand or revise a specific solution component, activating the communication KS to send a request to the tool shop for a completion date estimate for a new tool, etc.). A key feature of the IP3S architecture is its ability to support multiple control regimes, including highly interactive control regimes where the end-user decides which KS to invoke next as well as more autonomous control regimes where control heuristics are used to decide what to do next.

Our approach to developing and refining this module is an incremental one. The first version of the module will require the user to interactively make many of the control decisions. Over time, control heuristics will be developed to relieve the user of lower-level ("operational") control decisions, enabling him, when appropriate, to concentrate on higher-level ("tactical/strategic") decisions . The result will be a system where the user can select between different levels of interaction and different control regimes. This includes tight interaction regimes where the user imposes low-level decisions (e.g., specific selection of a process alternative, specific sequencing of two operations on a given machine, activation of a specific KS, etc.) as well as looser modes of interaction where the user interacts with the system through specification of *higher-level objectives/tasks* (e.g., requesting the system to look for a solution where the engineering costs associated with a specific order are lower than in the current solution, a solution where one or several orders are completed earlier, etc.), relying on the control heuristics to drive the search for one or several alternative solutions that meet the specified

objective(s). Examples of KS activation patterns required to support different scenarios are described in the following section.

## Scheduling Knowledge Source

This knowledge source is based on the Micro-Boss finite capacity scheduling system [Sadeh91a, Sadeh93b, Sadeh94a]. Micro-Boss relies on a new set of "micro-opportunistic" search procedures that constantly monitor resource contention during the construction or repair of the schedule and dynamically redirect the system's optimization efforts towards areas of the search space subject to the highest contention (i.e., groups of operations contending for critical resource/time intervals). These search procedures support predictive, reactive and interactive scheduling functionalities and have been shown to consistently yield significant improvements in schedule quality (i.e., due date satisfaction, lead-time and inventory performance) over multiple combinations of priority dispatch rules and release policies as well as over sophisticated bottleneck-centered scheduling techniques[1] .

## Process Planning Knowledge Source

This knowledge source is based on Raytheon's ICAPP generative process planner [Raytheon93a, Raytheon93b], a system currently in use at two of Raytheon's Government Group divisions. A key feature of this module will be its ability to develop and revise process plans while accounting for existing and projected resource commitment information posted on the blackboard.

ICAPP utilizes knowledge bases populated with raw stock configurations, process selection logic and manufacturing resource capabilities. Machine tool selection and tool path generation is done by invoking CUTTECH, a module developed by the Institute of Advanced Manufacturing Sciences (IAMS). Plans produced by ICAPP consist of:
- an ordered list of machining operations including recommended tooling, feeds and speeds
- process routing information,
- bill of materials.

## Analysis / Diagnosis Knowledge Sources

The IP3S approach is based on the general premise that the complexity of the combined process planning/production scheduling search space can effectively be reduced and solution

---

[1]Recently, the system was also customized for the scheduling of the Printed Wiring Assembly area at Raytheon's Andover facility, an environment with about 1,000 different part types, a volume of about 35,000 parts/month grouped in about 1,000 orders, and 148 resources grouped in 23 work centers.

quality enhanced (a) by using process planning considerations to help focus search within the scheduling sub-space and, conversely, (b) by taking into account scheduling considerations to quickly identify promising alternatives within the process planning sub-space. Analysis/diagnosis knowledge sources are central to achieving this integrated search behavior. They help identify sources of inefficiency in the current solution and determine how the solution can most effectively be improved (e.g., whether to generate an alternative process plan for a given part, to modify its current tooling requirements, reschedule operations on a critical machine, reallocate NC programmers to different machines, etc.). Analysis results are summarized on the blackboard, where they are used by the IP3S controller to automatically determine which subproblem to work on next (e.g., process planning or production scheduling sub-problem). They are also accessible through the system's GUI helping the end-user in his/her decisions. Below we briefly review some critical analysis/diagnosis KSs we are developing. It is expected that this set will continue to grow as we work on supporting more sophisticated integration scenarios.

- *Resource Utilization KS* : This KS will analyze existing resource allocations and compute utilization statistics for specified sets of resource/ time intervals. This information helps the Process Planning KS select among process alternatives and will later be used by the IP3S Controller to identify critical decisions on which to focus solution construction (e.g. determining that the first step in incorporating a new order in the existing solution should be to focus on a specific manufacturing feature that requires a tool already in high demand)

- *New Tooling Requirements KS* : Given an order for a new part, this analysis KS helps identify features of the part that are likely to require production of new tools or complex modifications to existing ones and hence may significantly delay production of the part.

- *NC Programming Requirements KS* : This KS is similar to the previous one but focuses on the identification of part features that may require significant NC programming efforts.

- *Critical Raw Material Requirements KS* : This KS is similar to the previous two but focuses on the identification of unusual raw material requirements that can possibly delay production of the part .

Future analysis/diagnosis KSs currently envisioned also include:

- *KSs to Identify Solution Inefficiencies/Opportunities for Solution Improvement* : These KSs will be specialized in the identification of specific inefficiencies/opportunities for improvement in the solution (e.g. a late order, an order whose lead-time seems particularly high, an order whose engineering costs seem particularly high, an underutilized resource, etc.)

- *Solution Improvement KSs*: Given a specific solution inefficiency, such a KS would help identify promising ways of improving the current solution. For instance, in the case of an order whose completion date is delayed due to contention for a bottleneck machine, a specialized KS could be called to explore alternative ways of improving the existing solution, e.g. modifying the critical order's process plan, freeing the bottleneck resource by modifying process plans of competing orders, etc. The KS would evaluate how attractive each one of these alternatives appears and post its results on the blackboard, where they could be used by the IP3S Controller or the user to decide which alternative to try first.

Communication Knowledge Source

This KS is intended to support communications with the outside, including the Andover tool shop, the enterprise-level planning system, suppliers, etc. Typical messages to be handled by this KS include incoming order messages received from the enterprise-level planning system, expected order completion dates sent to the enterprise-planning system, requests to the tool shop for estimates of the times required for producing or modifying tools, raw material replenishment messages sent to suppliers, etc.

## 4. OPERATIONAL SCENARIOS

Our initial work focuses on supporting relatively simple integration scenarios. An example of one such scenario to accommodate an incoming order into the existing process planning/production scheduling solution involves the following steps:

(1) the IP3S controller activates the Resource Utilization KS which posts resource utilization statistics on the blackboard (i.e., utilization of one or more resources over different time intervals),

(2) the controller activates the process planning KS, which uses resource utilization statistics posted on the blackboard to select among process planning alternatives with different resource requirements, and finally

(3) the controller activates the scheduling KS to incorporate the new order (with its process plan as posted on the blackboard by the process planning KS) into the existing production schedule.

Over time, more sophisticated activation patterns will be developed that will significantly enhance the ability of the facility to dynamically reconfigure itself in response to changing circumstances. This will include:

• *Activation patterns that support dynamic interleaving of process planning/production scheduling decisions* : Central to the proposed blackboard architecture is the notion of concurrent *opportunistic* process plan/production schedule construction/revision. Opportunistic problem solving stems from the ability to constantly adapt to the problem situation at hand, as characterized by information posted on the blackboard, and focus the problem solving effort on what appears to be the most critical set of decisions [HayesRoth79, Erman80, Stefik81, Ow&Smith88, Sadeh91a]. Here, examples of critical decisions can include selecting between process alternatives requiring highly utilized ("bottleneck") machines, deciding whether to query the tool shop to find out how long it would take to produce a particular tool, deciding how to best utilize a highly skilled NC programmer, etc. By dynamically focusing on the most critical set of decisions whether process planning or production scheduling decisions, opportunistic problem solving aims at quickly "anchoring" solution construction/revision and effectively reducing the number of alternatives to be considered by quickly steering the problem solving effort towards the most promising areas in the solution space.

Consider, for instance, a new order whose production involves two major sets of machining steps that can a priori be performed in either order (i.e. set1 before set2 or set2 before set1). Inspection of the tooling requirements of these two sets of machining steps might reveal that one of the two require modifying an existing tool, an activity expected to take 2 days. Early identification of this situation (e.g., by successively activating the "New Tooling Requirements" KS , then activating the process planning KS to refine the corresponding part of the solution and finally querying the tool shop via the communication KS to determine how long it will take to modify the tool) can help sequence the two sets of manufacturing steps, starting with the set that does not require the modified tool.

This early combination of process planning and production scheduling decisions may in turn strongly reduce the number of remaining process planning/production scheduling alternatives to be considered. This in turn can often translate into a better solution.

- *Activation patterns supporting both interactive and autonomous solution improvement scenarios*: another key aspect of the IP3S blackboard architecture is its ability to support both interactive and autonomous solution improvement scenarios. Here, solution inefficiencies and/or opportunities for improvement will be identified either through interaction with the user or directly by an analysis/diagnosis KS.

The system will then proceed to find one or several alternative solutions that improve on the current solution with respect to the specified criterion/criteria. Examples can include a group of orders whose completion dates should be improved, an order whose engineering costs appear too high (e.g., too many new tools need to be designed), raw material inventories that appear too high or lead-times too long, a process plan that uses a sub-optimal machine (e.g., an old machine that is difficult to calibrate or tends to break down), etc.

Given a solution improvement task (whether specified interactively by the user or defined by the system itself), the system will operate according to control heuristics tailored for that particular solution improvement task. The control heuristics will typically guide the solution improvement effort through three successive phases.

In a first phase, the system will attempt to identify sources of inefficiency in the current solution. For instance, in the case of an order whose completion date should be improved, the control heuristics may first activate an analysis KS that will attempt to identify the presence of possible bottleneck machines or tooling requirements that delay completion of the order in the current solution.

In a second phase, once one or several sources of inefficiency have been identified, the control heuristics will typically proceed and activate KSs to identify promising ways of getting rid of these inefficiencies. For instance, in a situation where processing of a critical order is

delayed in front of a bottleneck machine, the control heuristics may activate a second analysis KS to identify orders that could be replanned/rescheduled and hence allow the critical order to be processed earlier on that machine.

Finally, in a third phase, the control heuristics will select a specific option to improve the solution (e.g., modify the process plan of an order so that it no longer requires the bottleneck machine) and invoke the process planning and/or production scheduling KSs to modify the current solution accordingly.

Solution improvement will often be an iterative process. Several cycles may be required before reaching a satisfactory solution, as improvement with respect to one criterion may result in deterioration with respect to another. In the process, the system may (1) change its improvement criteria and switch to a different set of control heuristics, (2) abandon a given alternative and look for another way of improving the solution or (3) get back to the user for additional input (e.g., ask the user whether or not to continue trying to improve the solution).

## 5. SUMMARY AND CONCLUDING REMARKS

A key requirement to supporting agile manufacturing practices is ability to (1) rapidly convert standard-based product specifications into process plans and machine operations and (2) quickly integrate process plans for new orders into the existing production schedule to best accommodate the current load of the facility, the status and allocation of machines, fixtures and tool and the availability of raw materials. In contrast to traditional manufacturing practice, where process planning and production scheduling are treated as two independent processes, we are developing an Integrated Process Planning/Production Scheduling (IP3S) shell capable of supporting concurrent process planning/production scheduling solution development and revision. Our IP3S Shell is designed around an innovative *blackboard architecture* that emphasizes (1)*concurrent* development and dynamic revision of integrated process planning/production scheduling solutions, (2) the use of a *common representation* for exchanging process planning and production scheduling information, (3) *coordination* with outside information sources such as customer and supplier sites, and (4) *mixed initiative decision support,* enabling the user to interactively explore a number of tradeoffs. The shell is expected to significantly boost the ability of companies to adapt to rapidily changing conditions, both external and internal, and yield significant improvements in manufacturing performance (due date performance, leadtimes, inventories, resource utilization, engineering costs, etc.). The system, which is in its initial development stage, is scheduled for demonstration and evaluation in a complex, highly dynamic machine shop at Raytheon's Andover manufacturing facility.

# 6. REFERENCES

[Aanen88] Aanen, E. Planning and Scheduling in a Flexible Manufacturing System. PhD thesis, University of Twente, 1988.

[Bossink92] Gerhardus Johannes Bossink. Planning and Scheduling for Flexible Discrete Parts Manufacturing. PhD thesis, University of Twente, 1992.

[Erman80] - Erman, L.D., F. Hayes-Roth, V.R. Lesser, and D.R. Reddy, "The Hearsay-II Speech Understanding System: Integrating Knowledge to Resolve Uncertainty", *ACM Computing Surveys,* Vol. 12, No. 2 (June, 1980), pp. 213-254.

[Goldman95] Steven L. Godman, Roger N. Nagel, and Kenneth Preiss, "Agile Competitors and Virtual Organizations", Van Nostrand Rheinhold, New York, NY 1995.

[Goldratt80] Eliyahu M. Goldratt, "Optimized Production Timetable: Beyond MRP: Something Better is Finally Here", speech - APICS National Conf., Los Angeles, CA, 1980.

[Harrington74] Harrington, J.R. Computer Integrated Manufacturing. Industrial Press, NY, 1974.

[HayesRoth79] - Hayes-Roth, B. and F. Hayes-Roth, "A Cognitive Model of Planning", *Cognitive Science*, Vol. 3 (1979) pp. 275-311.

[Kerr91] Roger Kerr, *Knowledge-based Manufacturing Management*, Addison-Wesley, Singapore, 1991.

[Laliberty92] Thomas Laliberty, "Supporting Concurrent Engineering and Information Exchange via the STEP Standard", Master's Th., Rennselaer Polytechnic Institute, August 1992.

[Laliberty94] Laliberty, T., Lapointe, L., Bryant, R., "DICE MO - A Collaborative DFMA Analysis Tool", IEEE Proceedings, Third Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises, Morgantown, WV, April 1994.

[Lee92] Lee, H.L. "Managing Supply Chain Inventory : Pitfalls and Opportunities." *Sloan Management Review* , 1992.

[Nii86] Nii, H.P., "Blackboard Systems: The Blackboard Model of Problem Solving and the Evolution of Blackboard Architectures" *AI Magazine* 7 (2), 1986.

[Ow88] Peng Si Ow and Stephen F. Smith, "Viewing Scheduling as an Opportunistic Problem Solving Process", *Annals of Operations Research* , 12, 85-108, 1988.

[Orlicky75] Joseph Orlicky, *Material Requirements Planning*, McGraw Hill, NY, 1975.

[Raytheon93a] Raytheon Company, Metal Fabrication Computer Aided Process Planning - Technical Specifications, RAYCAM document 6685092A, 1993.

[Raytheon93b] Raytheon Company, Metal Fabrication Computer Aided Process Planning - User Manual, RAYCAM document 6685092B, 1993.

[Rembold86] U. Rembold and R. Dillmann. *Computer-Aided Design and Manufacturing.* Springer Verlag, 1986.

[Sadeh93b] Sadeh, N.M., S. Otsuka, and R. Schnelbach. Predictive and Reactive Scheduling with the Micro-Boss Production Scheduling and Control System. *Proc. IJCAI-93 Workshop on Knowledge-based Production Planning, Scheduling, & Control*, Chambery, France, Aug, 1993.

[Sadeh94a] Norman Sadeh. Micro-Opportunistic Scheduling: The MICRO-BOSS Factory Scheduler. In *Intelligent Scheduling*, Morgan Kaufmann Publishers, 1994, Chapter 4.

[Scheer91] A-W. Scheer. *CIM: Towards the Factory of the Future.* Springer Verlag, 1991.

[Smith94] Stephen F. Smith. OPIS: A Methodology and Architecture for Reactive Scheduling. In *Intelligent Scheduling*, Morgan Kaufmann Publishers, 1994, Chapter 2.

[Srinivasan94] Srinivasan, K., Kekre, S. and Mukhopadhyay, T. "Impact of Electronic Data Interchange Technology on JIT Shipments", *Management Science* , 1994. Forthcoming.

[Stefik81] - Stefik, M., "Planning with Constraints (MOLGEN: Part 1)", *Artificial Intelligence*, Vol. 16, No. 2 (May 1981), pp. 111-140.

[Swaminathan94] Swaminathan, J., N.M. Sadeh, and S.F. Smith. Impact of Supplier Information on Supply Chain Performance. Technical Report, The Robotics Institute, Carnegie Mellon University, 1994.